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College of Engineering
Mechanical and Industrial Engineering

MIE 415 Draft Report

1411
Guide Dog Robot

Sponsored by: Dynamic and Autonomous Robotic Systems Lab, UMass Amherst

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Executive Summary

For the past three years, the Dynamic and Autonomous Robotic Systems (DARoS) Laboratory at UMass Amherst has been conducting studies on guide dog robots. However, the lab's current research platform, the commercially available UniTree Go1 quadruped robot, lacks the ability to climb stairs. Although DARoS Lab has explored other commercial quadruped robots, none offer both good portability and stair-climbing capabilities at the same time. To address this gap, we present Vivo, our attempt at creating a prototype quadruped robot that offers both stair-climbing capabilities and portability by being able to fit within standard carry-on luggage dimensions. Vivo's legs are designed to closely mimic dog legs, which have been long proven to be effective at stair climbing. The leg lengths are also optimized for stair climbing based on kinematic analysis. Additionally, the robot collapses to smaller than carry-on luggage dimensions, making it portable for daily use.

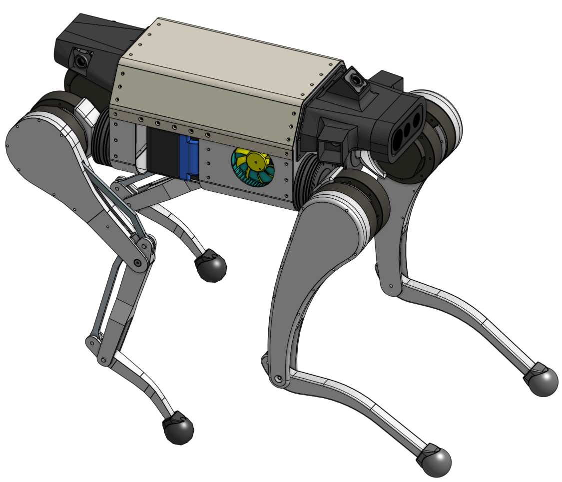


Figure 1. Final Design of Robot Guide Dog

Summary of Impact

Guide dogs are a popular aid for blind and low-vision (BLV) individuals as they provide the user with greater mobility, confidence, and independence. However, guide dogs have several drawbacks that make them unsuitable for some people. A new guide dog generally requires two or more years of training before they are capable of working effectively, which can cost over $40,000. Along with the upfront cost, dogs cost approximately $2,200 yearly for general care. Additionally, owning a dog comes with a lot of responsibility: they need consistent grooming, veterinary visits, and regular exercise. Finally, guide dogs typically work for only ten years, at which point the owner may have formed a strong bond, making it emotionally challenging to transition to a new dog. In contrast, a robot guide dog offers a lower barrier of entry for BLV individuals seeking a reliable mobility aid. Unlike traditional guide dogs, a robot guide dog could be purchased off-the-shelf without a waitlist or need for extensive training. Both the upfront and annual cost of a robot guide dog would be cheaper than that of a traditional guide dog, providing a more affordable and sustainable solution.

The contributions of our project are twofold. First, our robot serves as a research platform to study the use of guide dog robots for academic research. Second, our robot will help establish the foundation for testing the concept of a specialized quadruped guide dog robot, effectively acting as a prototype for future versions.

Introduction and Objectives

Objectives

The main objective of our project is to design and fabricate the body and legs of a power-efficient, lightweight quadruped robot guide specialized for blind and low-vision individuals, by offering legs capable of achieving stair climbing while ensuring a compact body for portability and user-friendliness. The DARoS lab has been using the Unitree Go 1 robot to explore computer vision applications for guide dog assistance, but significant hardware limitations—including short battery life (~15 minutes), inability to climb stairs, a narrow field of view, and hind leg interference—restrict its usability for blind and low-vision (BLV) individuals. Vivo is designed to address all these issues and offer chances for better computer vision studies.

Related Works

The use of robotic systems as a mobility aid for BLV individuals have been investigated as early as 1976, starting with the MELDOG project, in the shape of a wheeled robot (Tachi). Since then, robotic mobility aids have taken the shape of drones (Al Zavier), smart canes (Slade), and advanced wheeled robots (Guerreiro).

In recent years, the locomotion of quadruped robots have become robust enough for commercial use and have become an increasingly popular solution to automating undesirable tasks, such as safety inspection ("Industrial Inspection Solutions"). One of the underlying benefits of quadruped robots is their ability to traverse urban environments effectively, which makes them an attractive solution to mobility assistance for blind and low-vision individuals (Hwang).

Based on extensive qualitative research with guide dog users conducted by our sponsor, Hwang et. al, we aim to tackle the current limitations of portable quadruped robots for use as a mobility aid (Hwang). Currently, no commercially available quadruped robot matches the portability and stair-navigation abilities of a guide dog. Larger scale quadrupeds like the Boston Dynamics Spot robot and ANYbotics ANYmal C excel in stair-climbing, but their size makes them impractical for portable use. On the other hand, medium to small-scale robots such as the Unitree Go generation robots offer portability but lack the capability to traverse stairs of normal height (17.78 x 27.94 cm per ADA standards), which is required for a guide dog robot. This limitation creates a need for a compact quadruped robot that can traverse stairs.

With proper training, guide dogs have excellent street traversing capabilities and can climb stairs effortlessly ("Guide Dog Class Lectures: Working in Buildings"). This skill can be partly attributed to the anatomy of dog legs, which have been optimized for increased efficiency as a result of thousands of years of evolution. Inspired by the kinematics of legged animals, many quadruped robot designs incorporate bio-inspired mechanisms (Seok). Studies have shown that bio-inspired leg designs composed of redundantly actuated parallel mechanisms lead to higher efficiency in ground reaction force generation while also lowering power consumption, which is beneficial for both locomotion tasks and prolonging battery life (De Vicenti; Lee). Despite these advantages, a large number of commercially available quadruped robots today use a simpler two link, non-redundant leg design, which reduces mechanical complexity, but in turn sacrifices efficiency. To satisfy customer requirements for stair climbing, our leg design takes inspiration from the anatomy of dog legs.

Contributions of Each Team Member

Table 1. Team Member Contributions and Project Impact

Team Member/Role	Contributions
Ken Suzuki Team Lead	● Modeled initial concept in OnShape (body and legs) ● Communicated with team sponsors regarding progress, analysis, and design choices ● Conducted kinematic and inverse dynamics analysis of leg designs
Shaylyn Tavarez Analysis Lead	● Conducted structural by-hand analysis of robot legs ● Led Presentation for faculty analysis review ● Created shear force and moment diagrams for links ● Determined key design constraints ● Researched methods to perform structural analysis of robot
Salani Seneviratne Design Lead	● Researched methods to perform structural analysis of robot ● Performed structural by-hand analysis on the robot's leg designs under two conditions: ○ Equilibrium state ○ Maximum dynamic load ● Communicated with faculty for analysis review ● Conducted calculations to find the impact forces on the robot
Connor Delaney Fabrication Lead	● Performed FEA analysis of leg assembly ● Assisted team lead with statics analysis ● Assisted controls lead with interior configuration of robot ● Modified designs with the goal of improving manufacturability ● Writing for reports and AOIs
Georges Chebly Controls/Electrical Lead	● Optimized the body shape to make it manufacturable, compact, and able to fit within carry-on suitcase dimensions ● Helped team lead in the inverse dynamics analysis ● Worked on the interior of the robot ○ Decided on the electronics configuration ○ Designed mounts for electronics (cameras, computers…)

Peter White Evaluation Lead	● Helped with the preliminary and necessary research throughout the semester including material standards for Aluminum 6061-T6 and 1018 Carbon Steel, stair climbing and mobility analysis, and batteries ● Helped prepare for all AOIs, and write reports ● Presented the House of Quality and part of the PRP ● Performed ANSYS analysis on the shank of the robot leg (ended up not using ANSYS) ● Will soon help setup a URDF file for the robot and make an equivalent un-coupled back leg CAD model required for the URDF file analysis and assist with further by-hand calculations

Functional Decomposition

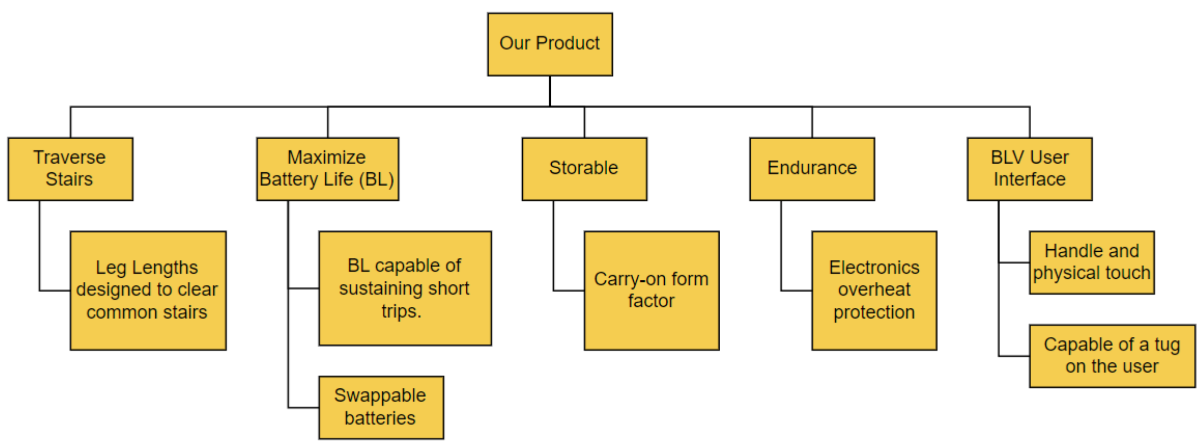


Figure 2. Functional Decomposition of Our Robot

In order to create a guide dog robot that meets the needs of a BLV user, the robot should be capable of performing five key functions, as illustrated in Fig. 1. First, the robot should be able to navigate urban terrain, which is crucial for guiding users during their travels. This includes overcoming common obstacles, such as stairs. To address this challenge the robot must have leg lengths and geometry capable of combating such obstacles. Second, the robot needs sufficient power to support typical outings, like trips to the grocery store.. This means the product needs to be designed to maximize battery life, in order to keep up the robots endurance for long trips, the electronic components need protection from overheating. For everyday travel, BLV users often use public transportation. In order for these experiences to go smoothly, the user must be able to store and carry the robot with relative ease. The last key function a robot dog must achieve is a user interface. The dog will require some sort of handle, physical touch features, and the ability to tug the user in the direction of travel.

Engineering Standards and Patents

Material Standards

The final design analysis was done using two material standards. The majority of the robot is made up of aluminum 6061-T6 and the transmission link is made of 1018 carbon steel. The ASTM standard specification for aluminum 6061-T6 material strength was used in analysis and the AISI/SAE 1018 carbon steel specification is set to be used in future analysis for steel components. The ASTM standard specifies aluminum 6061-T6 to have an ultimate tensile strength (UTS) of 260 MPa and yield strength (YS) of 240 MPa. The AISI/SAE mechanical properties for 1018 carbon steel are rated at a UTS of 440MPa and a YS of 370MPa.

Robotics Standards

ISO 13482 sets guidelines for the safety of personal care robots with respect to electrical, mechanical, and software aspects. These guidelines have helped pave the design process to ensure maximal safety and reliability. Following the guidelines for robot design, hard stop limits at each joint for singularity protection must be incorporated. Joints shall not be capable of crushing any body parts. User interface guidelines highlight the need for status indication and avoidance of sharp edges and points on the robot.

Manufacturing Standards

ISO 286 provides guidelines for tolerancing components in 2D drawings. As our sponsor intends to fund the manufacturing of robot parts through an overseas contract manufacturer, this standard will serve as the basis for communicating the geometry and tolerances of our components to them. This will be crucial for reliable operation of the legs.

Stair Standards

ADA § 504 & IRC § R311.7 outline the requirements for both residential and commercial staircases, including the maximum and minimum lengths for stair steps. Designing our robot to be capable of climbing stairs means it must be able to climb the tallest stairs as specified by these codes to ensure compliance with standards.

Patents

Patents were used to gain knowledge of the current competition and to obtain inspiration for our robot design. Boston Dynamics' Spot robot features an elbow joint actuated by a ball screw mechanism acting as a prismatic joint, which differs from belt driven or parallel link driven mechanisms that are popular in small scale quadruped robots (Potter). Although this mechanism is complex compared to other elbow actuation methods, it is highly efficient at transmitting force. The ANYmal C robot developed by ANYbotics features a limb between its top and bottom links, with a built-in Series Elastic Actuator that introduces passive compliance into the joint, which is a feature not present in traditional planetary gear box reduced brushless DC motor actuators (Scafato).

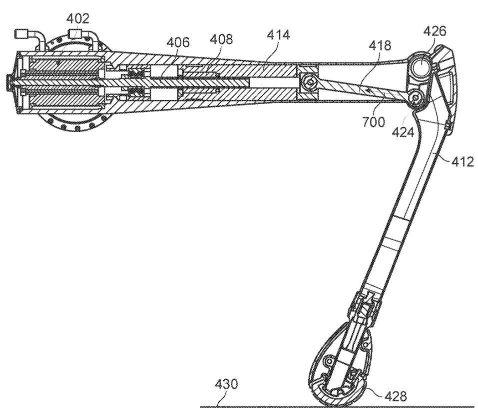


Figure 3. Leg design of Boston Dynamics' Spot robot (Potter).

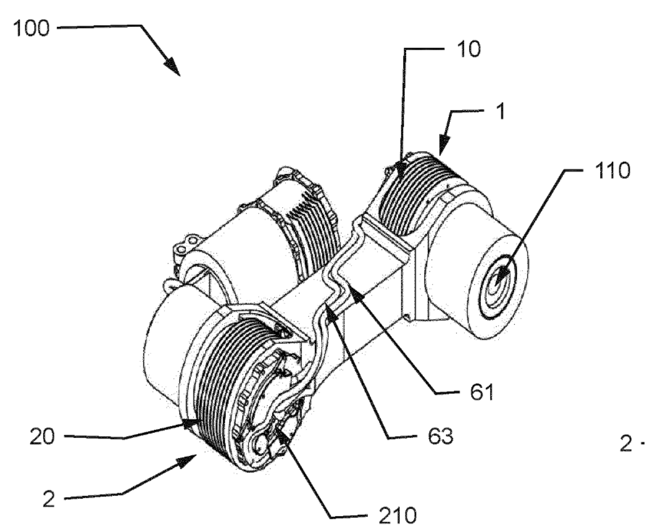


Figure 4. Limb design with incorporated series elastic actuators, developed by ANYbotics (Scafato)

Specifications

Table 2. Customer Requirements

Requirement	Weight (Importance: 1 (Least) → 6 (Most))
Storability/Small Size	4
Temperature Control	2
Operating Time	5
Portability	3
Cost	1
Hardware For Stair Climbing	6

The customer presented an initial list of requirements at the start of the semester which was refined through communication with the sponsor over the first month. The customer expressed that the final product must meet three major requirements: hardware cable of stair climbing, good battery life, and a portable form factor. From this, the team made these requirements of utmost importance as seen in Table 3. The requirement of a portable form factor is split into storability and portability since the customer emphasized that the quadruped should be lightweight, and be able to fold into airplane carry-on luggage size. In order for the robot to run effectively without overheating issues, temperature control was a must and was later decided as a customer requirement. Cost was put low on the list since the customer is open to financing the final product if the requirements are met, but the budget as with any project is still a consideration.

Table 3. Target Engineering Specifications

	Reachable Workspace (rise/go) $[m/m]$	Battery Capacity $[Wh]$	Mass $[kg]$	Storage Volume $[m^3]$	Operating Temperature $[C°]$
Ideal Values	$0.20/0.25$	288	≤ 21.5	< 0.45	< 55
Marginal Values	$0.18/0.28$	134	25	0.45	55

The engineering requirement specifications are presented in Table 2. The storage volume criterion was determined by using the average maximum collapsible carry-on volume in the United States of 55.88 x 35.56 x 22.86 cm^3. Achieving this form factor is necessary, but any value below this is ideal (Norcross). The operating temperature was determined as the maximum temperature the internal computers could withstand based on their respective data sheets. A ideal weight of 21.5 kg was imposed based on the weight of the Unitree Aliengo robot, which is slightly larger in size than our maximum allowable dimensions. The customer wanted a robot dog that has higher endurance than their previous robot, the Unitree Go1 which has a rating of 133Wh, so the marginal target is slightly above this value at 134Wh. The ideal value is an estimated maximum value of 288Wh, equivalent to a 0.76 hour battery life based on our proposed battery setup (Appendix C). The dog's ability to climb stairs is based on research out of the Italian Institute of Technology, which found that quadrupeds that have successful foot candidate positions that cover at least 20% of the "Go" surface climb stairs effectively. In accordance with the previously discussed IRC § R311.7 and ADA § 504 standards, we determined the ideal and marginal rise/go values that the robot must be able to climb. The ideal value was established using the higher rise/go ratio from the two standards, while the marginal value was based on the lower ratio.

Similar products were compared to further determine the necessities of each customer requirement. As seen in Table 4, our product has the best overall combination of the customer requirements compared to other options on the market. The UniTree Go1, a small-scale quadruped robot, excels in terms of storability and portability; however, it is unable to climb standard stairs.The UniTree Aliengo and Boston Dynamics Spot are both larger scale quadruped robots. This allows them to score well in operating time with larger batteries, and hardware for stair climbing with larger legs. However, since they are larger they fail to meet storability and portability requirements.

Table 4. Customer Requirements- Our Design Versus Competition (Order Note: 1 (Worst) → 5 (Best))

	Our Product	Boston Dynamics Spot	UniTree Go1	UniTree Aliengo
Storability	5	0	5	1
Temperature Control	3	5	3	4
Operating Time	3	3	2	5
Portability	5	1	5	4

Cost	4	1	5	2
Hardware for Stair Climbing	4	5	2	4

Design Selection and Solution

Leg Design

The leg designs were downscoped from the conventional, simpler two-link leg to a dog-inspired leg design to maximize system efficiency. As illustrated in Fig. 5a, our robot features different legs for the front and hind legs. The front leg features a two-link, two-degree-of-freedom leg, while the hind leg features a three-link, two-degree-of-freedom leg, with the middle and lower links coupled together via a redundant parallel mechanism. This three-link hind leg design was inspired by the MIT Cheetah 2 leg design, which is derived from a cheetah leg (Park). Compared to the legs of a golden retriever, our leg design simplifies the carpus (wrist) of the dog into a fixed ball, effectively removing one degree of freedom in each leg. By removing this actuated joint at the wrist, the total actuatable degrees of freedom is kept to 12, which is the number required for the robot to be compatible with our customer's custom locomotion controllers.

The leg lengths were downscoped from the approximate leg lengths of a golden retriever to an optimized leg length calculated with a stair-climbing evaluation method developed by Barasuol (Barasuol).

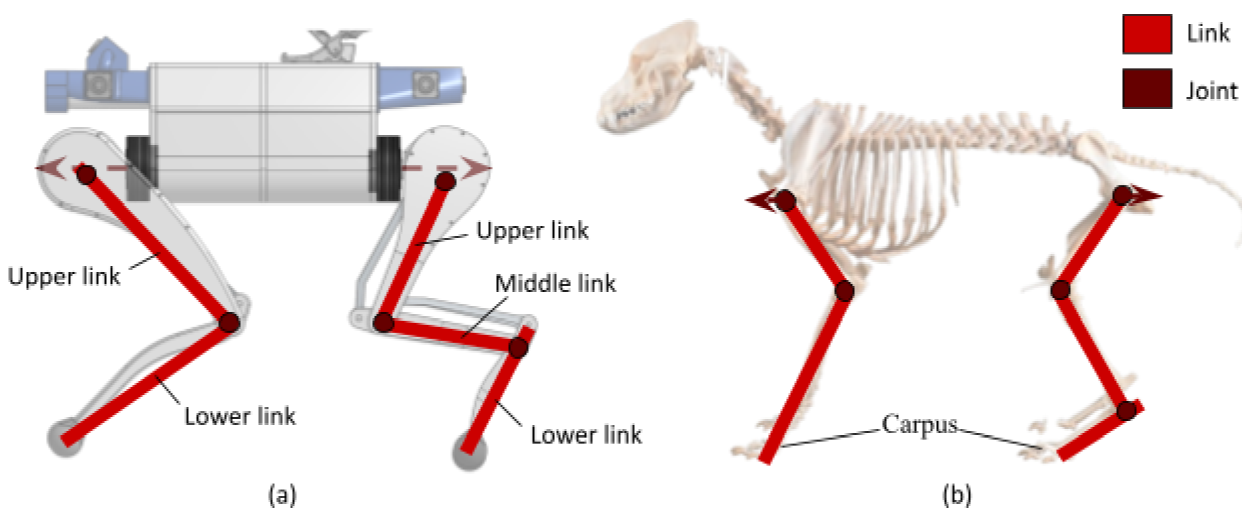


Figure 5. Comparison of (a) our robot's legs to (b) golden retriever legs (Museum of Veterinary Anatomy FMVZ USP).

The robot leg links must also withstand dynamic loads without failing. The stresses on the links were analyzed to determine the section modulus necessary for the links within the leg. Various cross-sectional areas were considered to figure out a lightweight design while maintaining strength.

Actuation Mechanisms

The leg actuation method was important to decide early on in order to guide our leg design and motor selection. Three systems were considered: transmission links, timing belts, and driving links directly with the motors. Out of these three, the first method to be discarded was driving links directly with the motor. While this system would be the simplest to implement mechanically, it has several drawbacks. Most notably, placing a motor at each joint would increase the mass and thus inertia of each leg. This results in motors that weigh more, take up more space, consume more power, and cost more. For these reasons driving links directly was discarded.

Timing belts to actuate the legs were the second option considered. Compared to directly attaching motors in each joint, timing belts offer several advantages. The moment of inertia in each leg decreases with a timing belt as the weight of the motor is being moved into the body of the robot. However, timing belts are hindered by slippage and experience decreased durability when improperly tensioned. If a timing belt is not properly tensioned during use, these issues build up overtime leading to premature failure (Layosa). It would be difficult for BLV individuals to perform this maintenance on their own, which motivated the decision to use transmission links.

Transmission links have several benefits for a quadruped robot of our size that make them the ideal choice. They allow all the motors in the robot to be located in the body, reducing the moment of inertia in the leg. Transmission links are also very durable which help reduce potential maintenance required in other systems. When the transmission link mechanism is configured in a redundantly actuated, parallel configuration, the elbow joint rotates the same angle as the motor output angle. This makes the controls of the robot almost as precise as the control of the motor can be. For these reasons, the transmission link was the selected actuation method.

(a) (b)

Figure 6. Elbow actuation mechanisms considered.
(a) Transmission link (RegulusRemains) (b) timing belt (Katz).

Motor Selection

Motors were selected based on the dynamic requirements of the robot. Additionally, using lower power motors was held paramount to prolong the robot's battery life. Since the robot is not intended to perform highly dynamic motions, the motor torque should be able to handle walking and stair climbing and nothing more. Brushless DC motors were selected due to their higher efficiency, lower operating noise, and higher angular velocity compared to other types of motors. They are also the most popular type of actuator used in legged robots today. The selected motors were the T-Motor AK60-6 and T-Motor AK80-9 for the hip roll, and hip pitch and flexion/extension, respectively. Through inverse dynamics calculations, the combined effort of the selected motors are able to withstand approximately twice the robot's estimated weight while standing.

Body Design

The body of the robot will contain all the electronic components to control the robot. It must have the strength to sustain loads from the legs while also being thermally conductive to prevent overheating of the electronics. The outer body will be constructed from aluminum sheets and plates for their high thermal conductivity and lower cost. Compared to other types of materials such as injection molded plastic, aluminum does not require the creation of a custom mold, which would be costly. While 3D printing the body is another option, it may compromise the strength of the structure due to the anisotropic properties of additively manufactured parts. In addition, the thermal conductivity of a plastic is higher relative to most metals, which compromises the heat dissipation. Aluminum was chosen over a metal like copper because of its high strength while also maintaining good thermal conductivity (“Copper, Cu; Annealed”).

The body design was developed to accommodate all the electronics while considering the robot's stair-climbing capabilities and fabrication efficiency. The electronics mounts inside the body will be placed symmetrically along the robot’s sagittal plane to keep the center of mass as close to the center as possible, ensuring equal weight distribution across the interior. Additionally, the robot’s belly thickness (i.e. the vertical distance between the hip axis and the lower body) must be minimized to maintain a higher clearance from the ground during stair climbing. To simplify the assembly, the body structure will be composed of four aluminum components (two plates, two metal sheets). Lastly, the computers will be positioned distant from each other to dispersed their generated heart to a wider area in the body interior to prevent buildup of high temperatures.

Detailed Design

Legs

- Leg lengths were determined using stair climbing evaluation method developed by Barasuol
  - Using residential stair codes as rise and go of stairs
  - (show picture of front and hind leg with final leg lengths)
  - (show picture of chart developed from stair climbing evaluation)
- link cross-sections were chosen based off the minimum section modulus and choosing a cross-section with low weight (ie. I-beam cross-section)
  - Following Aluminum and Steel standards when looking at yield strength values
  - Show final cross section → Leaning toward rectangular cross-section for transmission and potentially I-beam cross section for lower links and Hollow rectangle for upper to reduce weight
- A ball shaped foot to avoid complexity of an ankle joint
  - Material TPU for cost and meets necessary coefficient of friction to prevent slippage
- Transmission link system will be used
  - Transmission link lengths dependent on length of other links (upper, lower, etc.)
- Each joint in the leg includes a ball bearing to reduce friction in the joint.
  - Bushings were not used due to their higher friction, which increases energy use

Body

- Material- Aluminum
- Dimensions- just large enough to store electronics (show picture of body with final dimensions)
    - electronics are separated enough to prevent overheating
    - fits fan
    - (show picture of layout within the body)
- Thickness- Performed by hand analysis to determine necessary thickness to prevent high deflection of body from the weight of all electronics

Entire Body

- Final body dimensions fit in carry on luggage:
    - Show picture with final body dimensions
- Final weight of body is XX Kg (will be added once final design is completed)

Feedback From Sponsors and Mentors

- Met with sponsor biweekly for 30-45 minutes.
    - Incorporated feedback on some design choices such as the use of bearings versus bushings
    - Suggested using overlapping sheet metal to save space and add strength
- Met with Professor Sup
    - Advised us to conduct kinematic analysis of our legs designs to make sure they can reach the intended stair height
    - Advised us to take inspiration from biology for our leg designs
- Met with Professor Sun
    - Helped point out inconsistencies with statics analysis in legs
    - Suggested other parts of robot to analyze
        - Body deflection analysis
- Met with Professor Govind
    - Suggested against the use of FEA
    - Advised that simpler by-hand analysis would be sufficient

Cost Efficiency

- Cost optimization was considered throughout the design prices
    - Decided on 3D printing the electronics mounts inside the body
    - Went for 3D printable and detachable camera mounts

- Manufacturing methods were considered too — certain methods may be more cost-effective than others
    - Sheet metal is less expensive than manual milling and drilling as well as metal 3D printing

Detailed Engineering Analysis (Selected Design)

Structural Analysis

Assumptions

- Ignored the complex shape of linkages
- Ignored weight of linkages(negligible compared to the body)
- Point load on foot

Steps

1) FBD for each link within the leg
2) Find force equations at equilibrium
3) Utilize these force equations to determine the forces acting on the link during maximum dynamic load
    a) Estimated to be 2.2*weight, based on estimation by Bledt.
4) Create shear force and bending moment diagrams
5) Utilize maximum bending moment to find the section modulus of the link during max stress

$$\sigma_{max} = \frac{(M_{max} \times c)}{I_z} \qquad (1)$$

where σ_{max} is the maximum allowable stress, M_{max} is the maximum bending moment, c is the distance from neutral axis to outer surface and I_z is the moment of inertia.

$$FOS = \frac{\sigma_{yield}}{\sigma_{max}} \qquad (2)$$

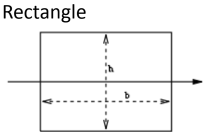
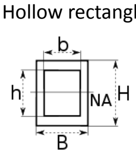
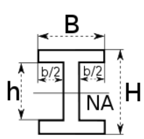
where FOS is the the desired factor of safety and σ_{yield} is the yield strength of the link.

$$S = \frac{I_z}{c} = \frac{M_{max}}{\sigma_{max}} \tag{3}$$

where S is the minimum section modulus of link to withstand the maximum stresses

6) Utilize this minimum section modulus to determine a cross-sectional area that will be lightweight, easy to manufacture, and withstand the maximum forces
    a) https://www.engineersedge.com/material_science/section_modulus_12893.htm

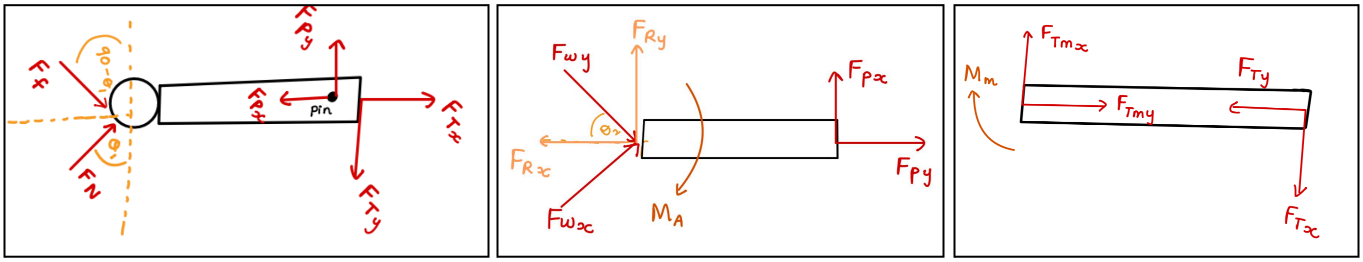
Table 5. Table showing equations to calculate section modulus for different cross sections

Shape of cross section	**Section modulus equation**
Rectangle 	$S = \frac{bh^2}{6}$
Hollow rectangle 	$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$
I-Beam 	$S = \frac{BH^2}{6} - \frac{bh^3}{6H}$

Front Leg

Static equilibrium - free body diagrams for the front leg

The static equilibrium calculations were done to find the force equations.



(a) (b) (c)

Figure 7. Free body diagrams for different front leg links
(a) Lower link (b) Upper link and (c) Transmission link

(a) Lower Link

Material Aluminum 6061

$$\Sigma y \ = \ 0; \ F_N cos\theta_1 + F_{Py} - F_f sin\theta_1 - F_{Ty} = 0 \tag{4}$$

$$\Sigma x \ = \ 0; \ F_N sin\theta_1 - F_{Px} + F_f cos\theta_1 + F_{Tx} = 0 \tag{5}$$

Considering the link to be a beam and using equations (4) and (5) to get the shear force and bending moment diagrams at the maximum dynamic load,

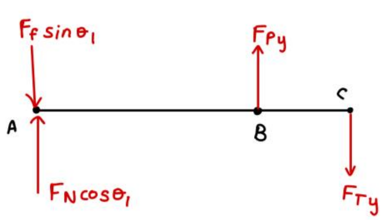


Figure 8. Simplified free body diagram

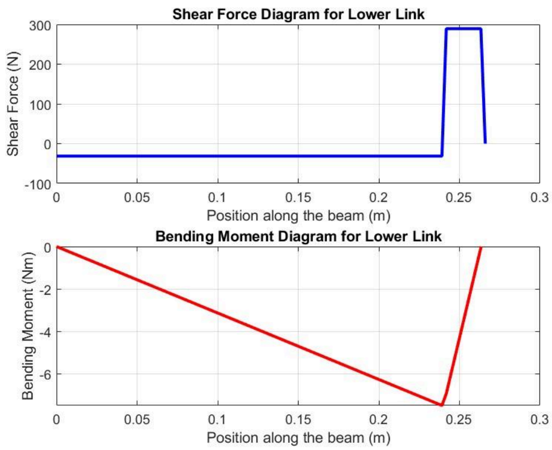


Figure 9. Shear force diagram and bending moment diagram of the lower link at maximum dynamic load

Design constraint section modulus of lower link must be greater than 0.31 mm^3

(b) Upper Link

Material: Aluminum 6061

Unique Assumptions:

- Point load from weight on screws
- Assumed fixed support at screws when in equilibrium

$$\Sigma y = 0; \quad F_{Wx} sin\theta_2 + F_{Wy} cos\theta_2 - F_{Py} = 0 \tag{6}$$

$$\Sigma x = 0; \quad F_{Wx} cos\theta_2 - F_{Px} - F_{Wy} sin\theta_2 = 0 \tag{7}$$

Considering the link to be a beam and using equations (6) and (7) to get the shear force and bending moment diagrams at the maximum dynamic load,

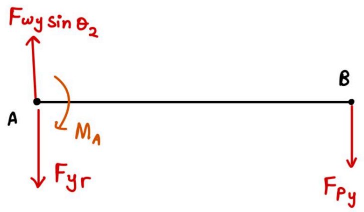


Figure 10. Simplified free body diagram

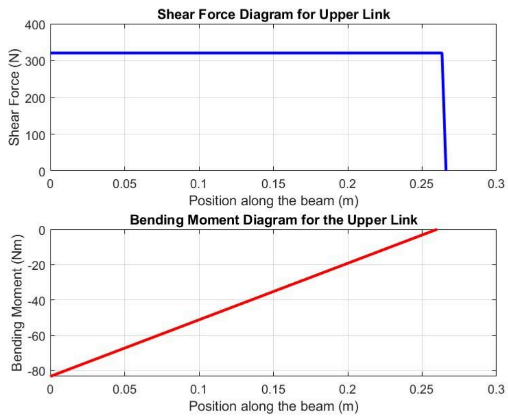


Figure 11. Shear force diagram and bending moment diagram of the upper link at maximum dynamic load

Design Constraint: section modulus of the upper link must be greater than or equal to 3.47 mm^3

(c) Transmission Link

Material: Steel

Unique Assumptions:

- Used the moment of the motor as the moment acting on the link

$$\Sigma y = 0; \; F_{Tmy} - F_{Ty} = 0 \tag{8}$$

$$\Sigma x = 0; \; F_{Tmx} - F_{Tx} = 0 \tag{9}$$

Considering the link to be a beam and using equations (8) and (9) to get the shear force and bending moment diagrams at the maximum dynamic load,

Figure 12. Simplified free body diagram

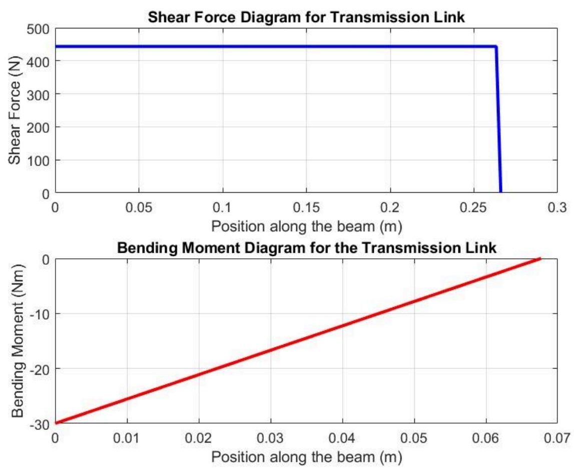


Figure 13. Shear force diagram and bending moment diagram of the transmission link at maximum dynamic load

Design Constraint: section modulus of the transmission link must be greater than or equal to $2.38\ mm^3$

In addition to the analysis provided above, we are currently performing by- hand analysis for the hind leg, which will be included in our report once finalized.

A buckling analysis will also be conducted to evaluate the stability under compressive loads. However, to validate our by-hand calculations, we will use ANSYS simulations for both legs, providing a comprehensive confirmation of the structural integrity.

Impact Force Calculation

These calculations are done based on a situation where the carry-on luggage with the robot is dropped from an overhead cabinet of an aircraft.

Assumptions:

- Maximum height to be the height from the floor of the aircraft to the overhead cabinet height (("How Are Overhead Bins Being Modified?")
- Neglecting air resistance
- Ignoring the weight of the carry on suitcase

Using energy conservation between the floor of the aircraft and height of the cabinet,

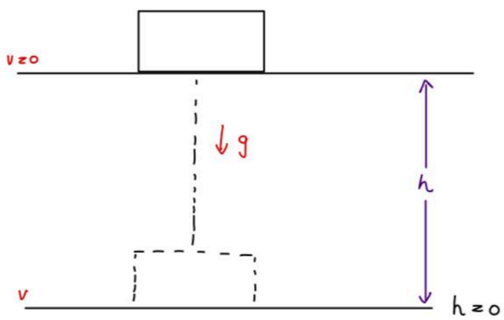


Figure 15. Diagram illustrating the free fall of the robot from the over head cabinet of the aircraft

$$Total\ potential\ energy\ of\ the\ system\ =\ Total\ kinetic\ energy\ of\ the\ system$$

$$\frac{1}{2}mv_0^2 + \frac{1}{2}mv_1^2 = mgh_0 + mgh_1 \tag{10}$$

where m is the mass of the robot, g is the gravitational acceleration, v_o is the initial velocity, v_1 is the final velocity, h_0 is the initial height and h_1 is the final height.

Since $v_o = 0$ and $h_1 = 0$, eq (10) is simplified to,

$$v_1 = \sqrt{2gh_0} \tag{11}$$

where g = 9.81 m/s^2 and h_0 = 2.1336 m (84 inches)

Therefore equation (11) gives v_1 (velocity when the object hits the ground) = 6.47 m/s.

Using F = ma, to find the impact force at collision with the ground,

$$F = ma = \frac{m\Delta v}{\Delta t} = \frac{m(v_2 - v_1)}{\Delta t} \tag{12}$$

where F is the impact force, v_1 is the velocity when it hits the ground, v_2 is the velocity when it decelerates to stop after hitting the ground and Δt is the time taken for the collision (time taken for the velocity to come to zero).

Assuming the time for collision to be 200ms, considering the mass to be 15 kg (mass of the robot) and v_2 = 0, from equation (12), we get the impact force to be, 485.25 N.

The impact force will be used to find whether the joints and legs of the robot can withstand such forces. Final calculations and verifications will be added once complete.

Deflection Analysis on the Body

The bottom sheet metal, which supports the weight of the batteries and electronics, was modeled as a fixed beam. This configuration is appropriate as the sheet metal is securely screwed into an aluminum plate at both ends and in all directions, creating fixed boundary conditions.

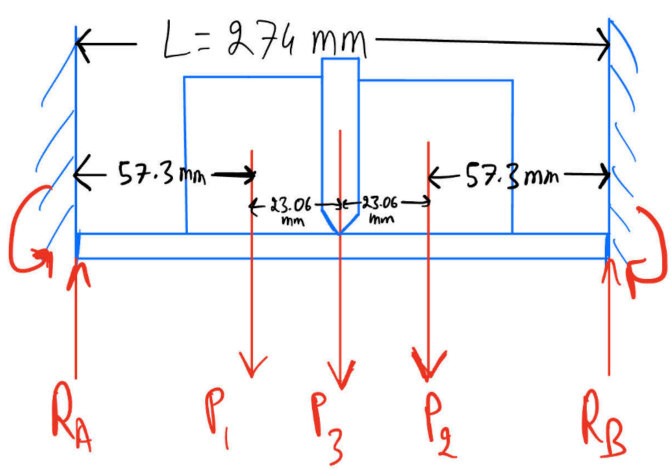
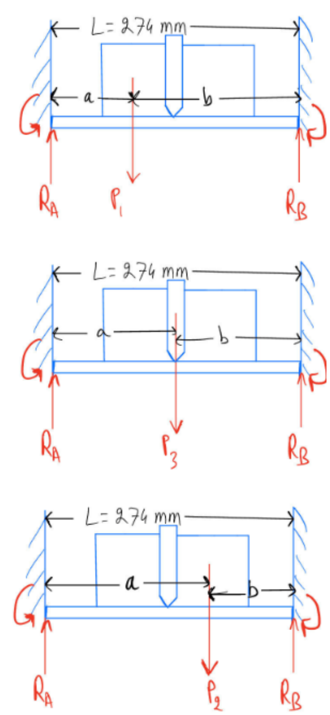


Figure 14. Free body diagram of the body



The body of the robot is designed to symmetrically house all electronic components. The main heavy components considered in the analysis include:

Two 24V 6Ah Kobalt batteries, each weighing 0.563 kg.
A Jetson computer weighing 1.095 kg.

The Jetson computer is mounted on a PLA structure attached to the center of the body. For simplicity, we assumed that the combined weight of the Jetson computer, PLA structure, and aluminum sheet acts as a point load at the center of the beam.

Our primary objective is to evaluate the deflection of the sheet metal under these concentrated loads. Using the deflection formula for a point load on a fixed beam, we calculated the deflections at three distinct points where the loads are applied:

- P1 is the weight of battery one.
- P2 is the weight of battery two.
- P3 is the weight of PLA structure, sheet metal, and computers.

The formula of deflection at a point load is:

$$\delta = \frac{P \cdot b^3 \cdot a^3}{3EIL^3} \tag{13}$$

Figures for each load are represented on the right.

Using the method of superposition (Juvinall, 130), adding up the deflections experienced at any point load would be a quick and efficient estimation for the total deflection:

$$\delta_{total} = \delta_1 + \delta_2 + \delta_3 \tag{14}$$

Dynamics Analysis

- Configured leg links to have joint limits probable for walking (based on joint angle data of similarly sized quadruped robots)
- Derived the forward kinematics and jacobian of each leg
- Set the ground reaction force of one leg to be half of the robot's weight
- Used virtual work equation $\tau = J^T F_{tip}$ to find the motor torques required to hold up the half the robot's weight on a single leg

Kinematic Analysis:

- Inverse kinematics analysis was conducted on each leg design to evaluate their stair climbing capability using the stair climbing evaluation method developed by Barasuol (Barasuol)
- To implement the stair climbing evaluation method the forward kinematics were derived for each leg design, as well as its jacobian matrix
- Subsequently, an inverse kinematics solver was created for each leg using Newton-Raphson to calculate the joint angles required to reach the desired footstep location
- Kinematic goal: Maximize the coverage of the leg on the stairs. At a minimum, the legs must be able to reach 20% of the *Go* surface
- Kinematic analysis algorithm is displayed in Fig. 17, and a detailed diagram of the stair climbing evaluation setup is shown in Fig. 16.

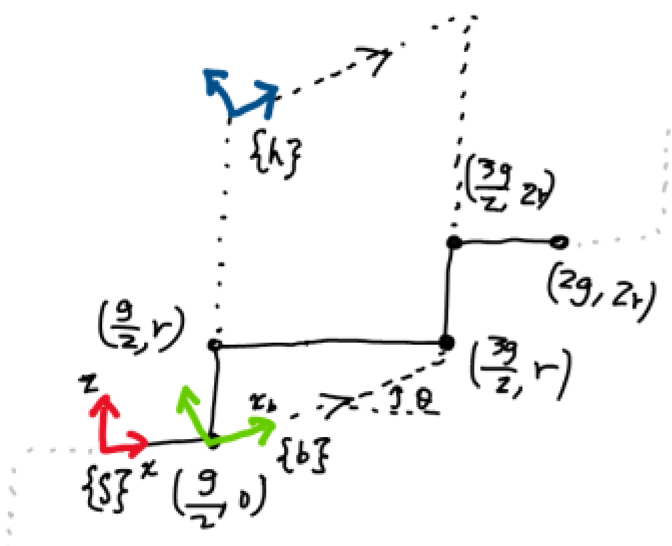


Figure 16. Stair climbing evaluation method diagram (Barasuol)

```
C/C++
Input: Leg dimensions, staircase dimensions
Output: Average percent coverage on staircase surface

for each body height do
       for each hip position in x_b do
              for each staircase increment do
                     solve inverse kinematics in footstep location i
                     if inverse kinematics fails or joint limit is reached
                            failed footstep location
```

```
                    else do
                          successful footstep location
             calculate average coverage in current hip position
      if average footstep coverage in body height < 20 percent
                    break
// Body height that corresponds to the maximum coverage is deemed the optimal stair
climbing height
```

Figure 17. Pseudocode for stair climbing evaluation method (Barasuol)

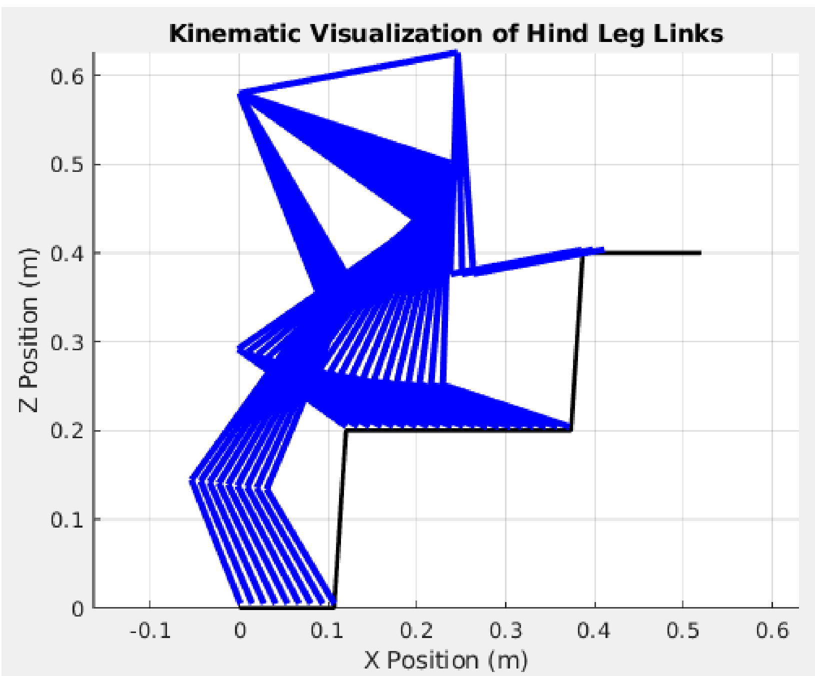
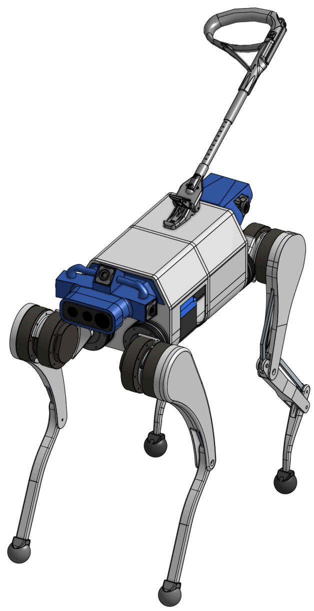


Figure 18. Kinematic visualization of hind leg at one hip height

Final Design

Present the final design through visuals and narrative, including engineering drawings, CAD model renderings, and photos of the production-level design and proof-of-concept prototype. Describe the design intent behind each feature and function of the final product. Note that the hardware prototype serves as a proof-of-concept to validate one or more design aspects and may differ from the CAD model.



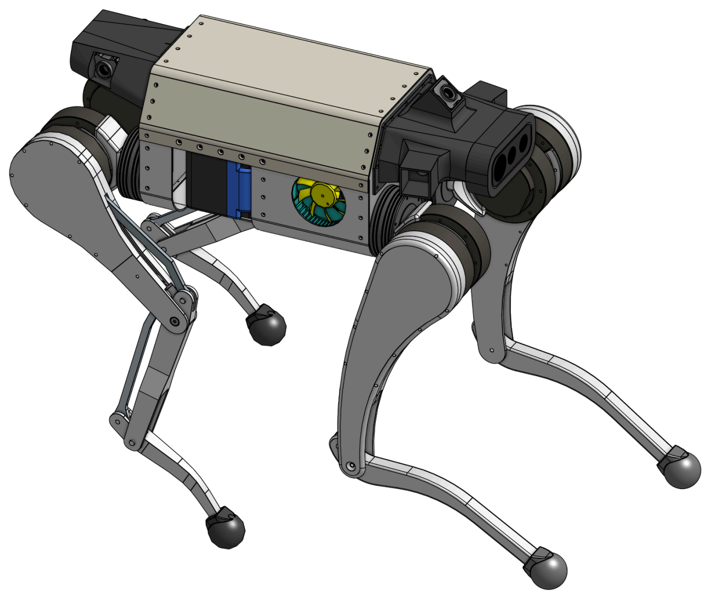


Figure 19. Full Body Final Design

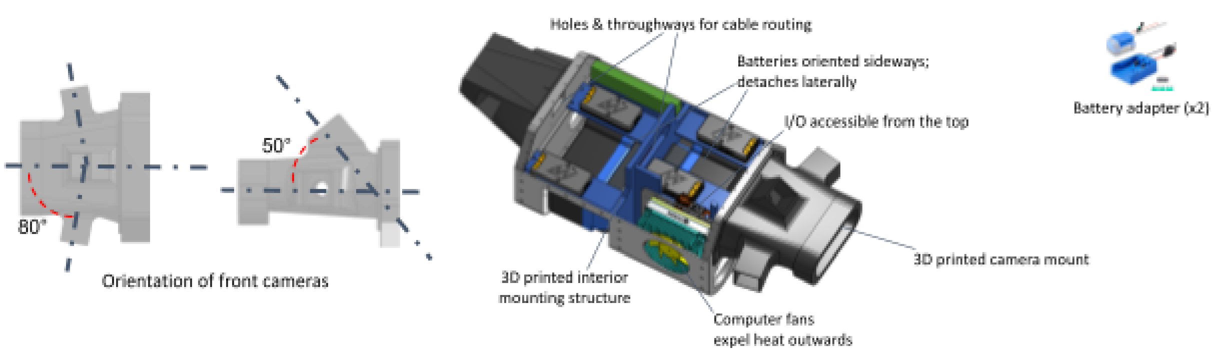


Figure 20. Internal Layout of Final Design

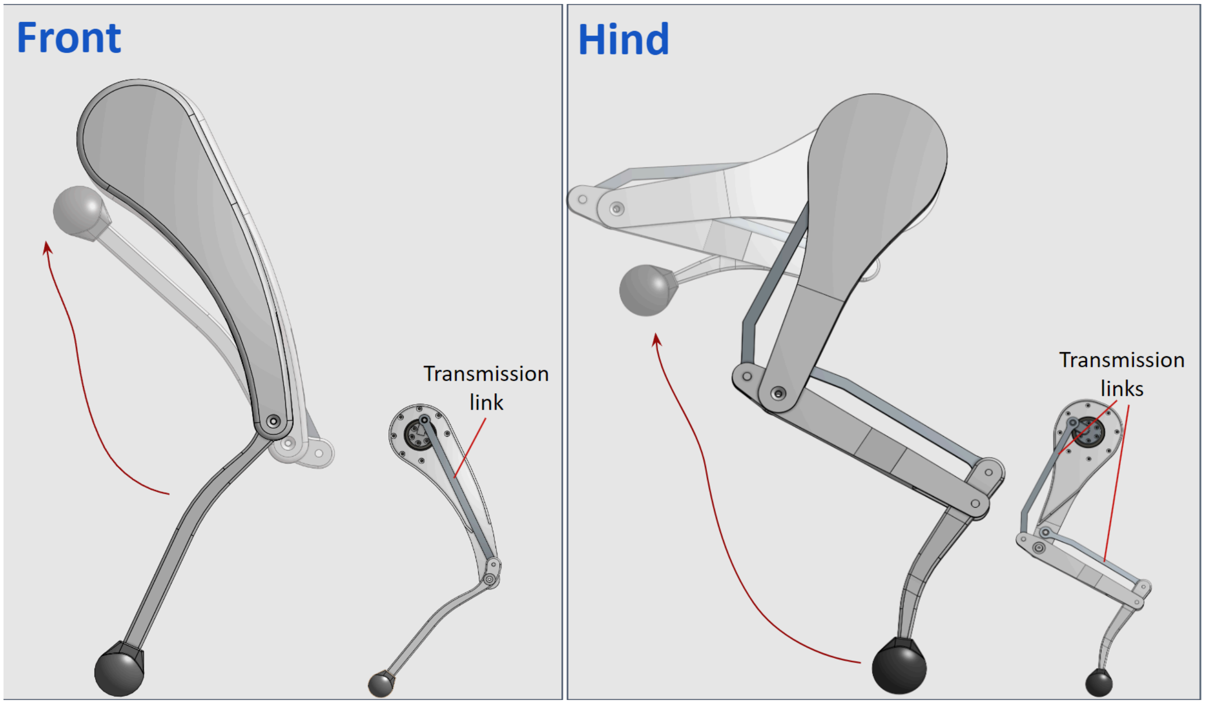


Figure 21. Leg Final Design and Actuation

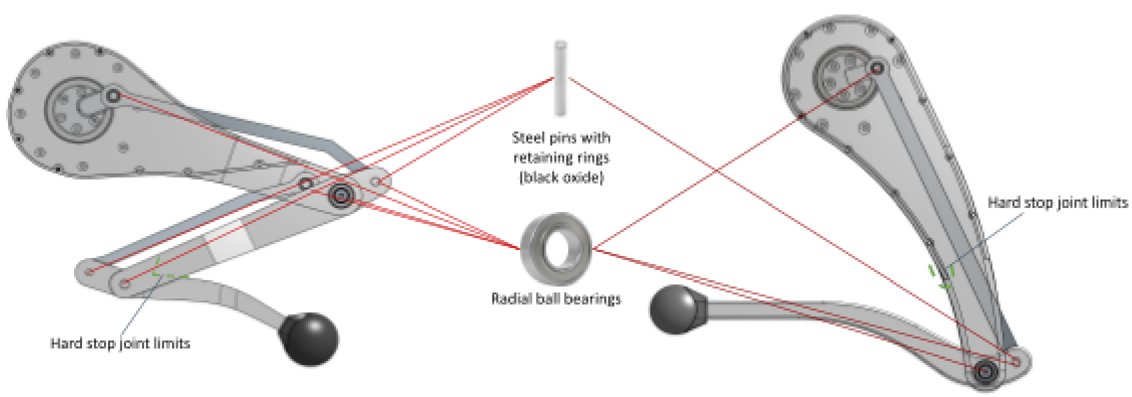


Figure 22. Internal Leg Mechanism

Design Evaluation (Complete it)

- Evaluate whether joints move with a smooth dynamic motion
- Evaluate the ability of the robot to climb stairs and walk down hallways
- Evaluate battery life under constant use
- Measure final weight of assembled robot
- Check that the max temperature of CPUs meets our engineering standards (Table 2)
- Check final dimensions and verify the design meets at least marginal requirements for storability

Performance Evaluation

- Stair climbing assessment with PhD student
- Mass of final assembly
- Battery life under constant use (typical gait speed)
- Max temperatures of CPUs
- Final collapsed dimensions

Discussion

Differences between the actual performance of the design and its intended performance (i.e., final specifications versus target specifications) should be noted. Was the project successful? If not, what went wrong? What were the lessons learned?

Conclusions and Recommendations (Outline)

Integrative Experience

Reflect on the Integrative Experience overview and requirements for this
course outlined in the syllabus. Summarize how this project has or has not satisfied the University's Integrative Experience requirement.

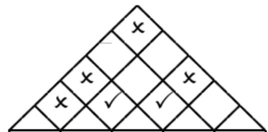
APPENDIX A: Draft Bill of Materials for Prototype

Vivo - Guide Dog Robot									
No.	Item Name	Details	Count	Price Per Item	Total Price	Supplier	Part No.	URL	Notes
1	Deep Groove Ball Bearing	Small, Double Shielded, 440C Stainless Steel	12	$7.92	$95.04	MiSUMi USA	SB676ZZ	URL	Bearings for legs
2	Precision Pivot Pins	Straight, Retaining Rings	2	$18.45	$36.90	MiSUMi USA	CCGH6-14	URL	Pins for legs
3	Precision Pivot Pins	Straight, Retaining Rings	2	$18.45	$36.90	MiSUMi USA	CCGH6-27	URL	Pins for legs
4	Precision Pivot Pins	Straight, Retaining Rings	2	$18.45	$36.90	MiSUMi USA	CCGH6-27	URL	Pins for legs
5	Ball Bearing	Sealed, Trade No. 6800-2RS, for 10 mm Shaft Diameter	12	$6.63	$79.56	McMaster-Carr	5972K275	URL	Bearings for legs
6	External Retaining Ring	for 6 mm OD, Black-Phosphate 1060-1090 Spring Steel	1	$8.10	$8.10	McMaster-Carr	98541A114	URL	Retaining rings for fastening pin
7	AK80-9 48V Robotic Dynamic	KV100	8	$724.90	$5,799.20	RobotShop	RM-CUBE-008	URL	Hip pitch motors
8	AK60-6 V1.1 24V Exoskeleton Module-KV80	KV80	4	$373.90	$1,495.60	RobotShop	RM-CUBE-002	URL	Hip roll motors
9	CANdle HAT		4	€149.00	€596.00	MAB Robotics		URL	USB to CAN bridge
10	MD80 v3.0 motor controller		12	€220.00	€2,640.00	MAB Robotics		URL	Motor controllers

APPENDIX B: House of Quality

✕	Negative Influence
✓	Positive Influence

"+" Positive Relationship
0 - Average relationship
"-" Minimum Relationship



Customer Attributes, Needs, Requirements, or Demanded Quality	Relative Weight	Battery Capacity	Weight	Storage Volume	Reachable Workspace (rise/go)	Operating Temperature	Now: My Product	Now: Spot (Boston Dynamics)	Now: Go1 (UniTree)	Now: Aliengo (Unitree)
Storability/Small Size	4	+	+	+	0		5	0	5	1
Temperature Control	2	0				+	3	5	3	4
Operating Time	5	+	+			0	3	3	2	5
Portability	3	0	+	0	0		5	1	5	4
Cost	1	+		-	-		4	1	5	2
Hardware For Stair Climbing	6		+	0	+		4	5	2	4
Direction of Improvement		⇧	⇩	⇩	⇧	⇩				
Measurement Units		W*h	kg	m^3	m/m	°C				
Spot (Boston Dynamics)		564	33.8	1	0.32/ 0.35	55				
Go1 (Unitree)		133.2	12	.02	0.12/ 0.27	-				
AlienGo (Unitree)		317.1	19	0.03	0.32/ 0.35	-				
Ideal Target Specification Values		288	≤ 21.5	< 0.454	0.20/ 0.25	< 55				
Marginal Target Specification Values		134	≤ 25	0.454	0.18/ 0.28	55				

APPENDIX C: Battery Calculations

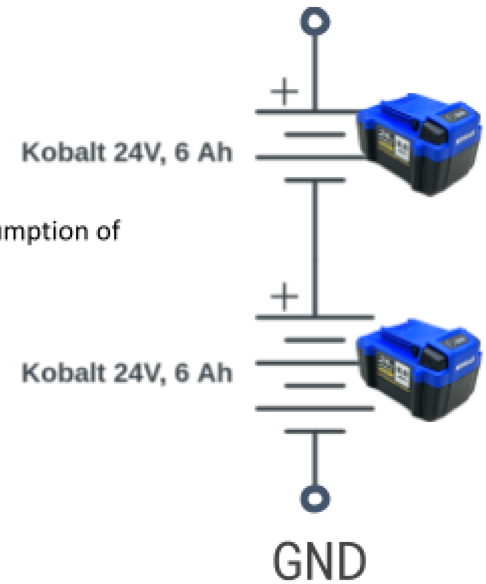
$$V = 24\ [V]$$ battery voltage

$$C = 6\ [Ah]$$ battery capacity

$$P_{consumed} \approx 400[W]$$ estimated power consumption of ANYmal robot (Hutter)

$$T = \frac{2 \cdot V \cdot C\ [Whr]}{P\ [W]} = \frac{2 \cdot 24 \cdot 6}{400}\ [hr]$$

$$\boxed{T = 0.72\ [hr]}$$ battery life



APPENDIX D: References

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